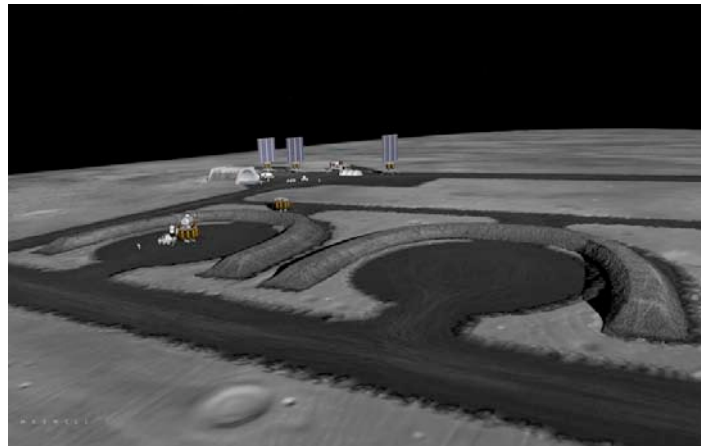
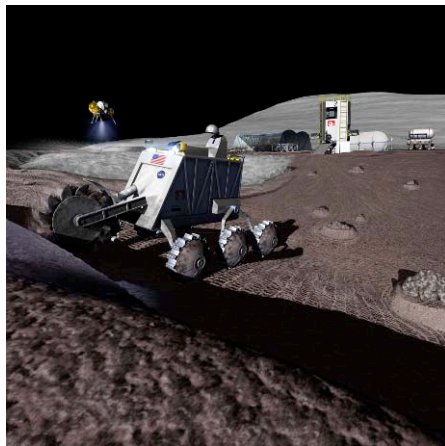




# NASA In-Situ Resource Utilization (ISRU) Development & Field Testing



*Presentation to the  
HAWAII'S AEROSPACE INDUSTRY: THE NEXT FRONTIER  
August 21, 2008*

*Hawaii State Capital Auditorium*

William Larson/NASA Kennedy Space Center  
Gerald Sanders/NASA Johnson Space Center



# What is Lunar In-Situ Resource Utilization (ISRU)?



**ISRU involves any hardware or operation that harnesses and utilizes ‘in-situ’ resources to create products and services for robotic and human exploration**

## In-Situ Lunar Resources

- ‘Natural’ Lunar Resources
- Discarded Materials

## Lunar ISRU Products and Services

- Excavation, Site Preparation, and Outpost Deployment/Emplacement
- Mission Consumable Production
- Outpost Growth and Self-Sufficiency

## Benefits of ISRU

- Increased science and exploration hardware (instead of consumables)
- Increased safety, crew exploration time, and self-sufficiency
- Technology spin-in/spin-offs help recycling on Earth & space economy

## Potential Missions Include:

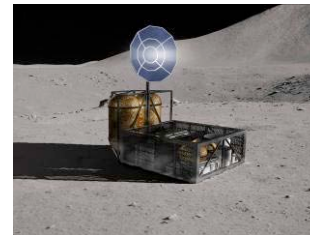
Precursor Ground  
Truth Missions



Precursor Oxygen Extraction  
from Regolith Missions



Outpost Oxygen  
Extraction from Regolith



Outpost Site  
Preparations





# Consumable Production for Lunar Outpost



## ■ Oxygen (O<sub>2</sub>) Production from Regolith

- 1 MT/yr production rate for ECLSS/EVA closure
- 0.9 MT/yr to make water for ECLSS/EVA closure with lander propellant scavenging
- 10 MT/yr production rate during Outpost operation would also support refueling 2 ascent vehicles per year to further increase payload delivery capability
- Options include: Hydrogen reduction (1 to 5% kg O<sub>2</sub>/kg bulk regolith), Methane Carbothermal reduction (10 to 28%), and Molten electrolysis (up to 40%)

## ■ In-Situ Water Production

- 1 MT/yr water needed for life support/EVA closure
- ~3 MT water needed habitat radiation shielding (3 habitats of 1000 kg each)
- ~225 kg water needed for each Small Pressurized Rover thermal/radiation system
- Options include:
  - Scavenge hydrogen from each LSAM descent stage after landing and add to in-situ oxygen to make 1 MT/yr of water (40 to 60 kg of H<sub>2</sub> remains after all O<sub>2</sub> is consumed to make water)
  - Post-ECLSS crew waste/plastic trash processing to complete extraction of water
  - Polar water/ice extraction and processing only needed if large scale in-situ propellant production is used incorporated into the architecture

## ■ In-Situ Methane Production

- ~2100 kg/yr supports refueling 2 ascent vehicles per year.
- Capability can be used to initially supports LSAM Ascent 'top-off' in case of leakage, power loss, or increased payload to orbit before completely refueling ascent vehicle
- Options include:
  - Utilize methane produced by habitat life support system (400-500 kg/yr for crew of 4)
  - Process plastic trash and crew waste with in-situ oxygen to make methane



# Lunar Regolith Processing Options Under Consideration



## Lunar Mare Regolith

### Ilmenite - 15%

FeO•TiO <sub>2</sub>	98.5%
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### Pyroxene - 50%

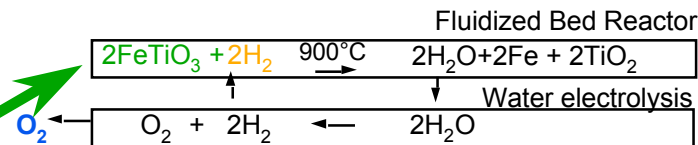
CaO•SiO <sub>2</sub>	36.7%
MgO•SiO <sub>2</sub>	29.2%
FeO•SiO <sub>2</sub>	17.6%
Al <sub>2</sub> O <sub>3</sub> •SiO <sub>2</sub>	9.6%
TiO <sub>2</sub> •SiO <sub>2</sub>	6.9%

### Olivine - 15%

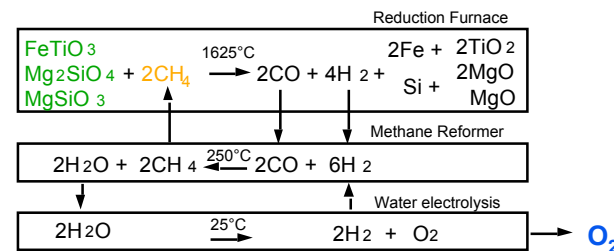
2MgO•SiO <sub>2</sub>	56.6%
2FeO•SiO <sub>2</sub>	42.7%

### Anorthite - 20%

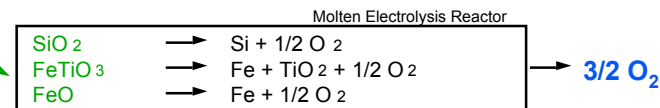
CaO•Al <sub>2</sub> O <sub>3</sub> •SiO <sub>2</sub>	97.7%
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Hydrogen Reduction of Ilmenite/glass Process



Methane Reduction (Carbothermal) Process



Molten Electrolysis

## Solar Wind & Polar Ice/H<sub>2</sub>

Hydrogen (H <sub>2</sub> )	50 - 150 ppm
Helium (He)	3 - 50 ppm
Helium-3 ( <sup>3</sup> He)	10 <sup>-2</sup> ppm
Carbon (C)	100 - 150 ppm
Polar Hydrogen H <sub>2</sub> O/H <sub>2</sub>	1 - 10%

Volatile Extraction



# ISRU Excavation & Oxygen Production Examples & Analogies



- Excavation rates required for 10 MT O<sub>2</sub>/yr production range based on extraction efficiency of process selected and location
  - Hydrogen reduction at poles (~1% extraction efficiency): 150 kg/hr
  - Carbothermal reduction (~14% extraction efficiency): 12 kg/hr
  - Electrowinning (up to 40%): 4 kg/hr
- Laboratory tests showed high excavation rates of to 250 kg/hr for small bucket wheeled vehicle (<150 kg)



CRATOS  
rover at GRC

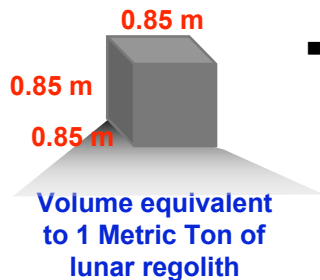


IR&D rover  
at LMA

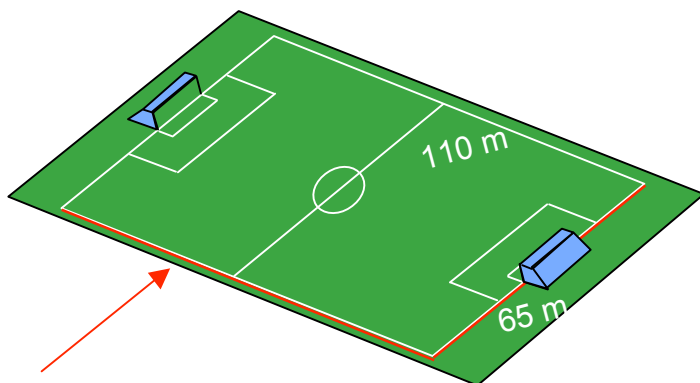
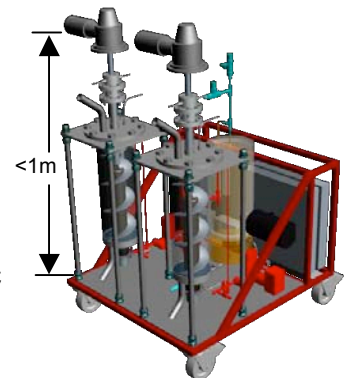


Bucketwheel  
at NORCAT

150



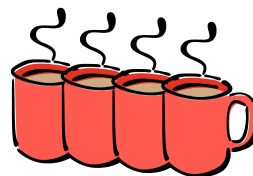
- Oxygen Processing Reactors are not large, even for 1% efficient systems (H<sub>2</sub> Reduction at poles with no beneficiation)
  - Module sized for 670 kg O<sub>2</sub> per year
  - Each reactor processes 10 kg/batch of regolith
  - Each reactor is 30" L x 8" D (76 cm x 20 cm)



**10 MT of oxygen** per year  
requires excavation of a soccer  
field to a depth of **0.6 to 8 cm!**  
(1% & 14% efficiencies)



**1 MT of oxygen** per year requires an  
excavation rate of **<1/2 cups per minute!**  
(1% efficiency - 70% light)  
(worst case)



**10 MT of oxygen** per year  
requires a regolith excavation rate of  
**~4 cups per minute!**



**300 MT of oxygen** per year requires  
a regolith excavation rate of  
**~10 cups per minute!**  
(14% efficiency - 70% time-polar region)



# ISRU Development Strategy



- **Develop ISRU Technology and Systems in 4 Phases** (2-4 years each phase)
  - Phase I: Demonstrate Feasibility
  - Phase II: Evolve System w/ Improved Technologies
  - Phase III: Test and Modify for Lunar Environment Applicability (1/6-g, vacuum, etc.)
  - Phase IV: Develop 1 or more systems to TRL 6 Before Start of Flight development
- **Coordinate development of ISRU Technologies and Systems with Other Surface Elements**
  - Identify common requirements, processes, hardware, and operations
  - Coordinate development of hardware to align Project schedule & milestones
- **Utilize laboratory and analog site demonstrations to:**
  - Demonstrate needed capabilities and operations for Lunar Outpost and technology/system 'customers'
  - Demonstrate evolution and incremental growth in technologies and systems for Capabilities (ex. digging deeper); Performance (ex. lower power); and Duration (ex. more autonomy or more robustness).
  - Perform joint hardware and operation tests with other Surface Element Projects
  - Develop partnerships and relationships across NASA and other US government agencies, and with International Partners, Industry, and Academia
- **Be prepared to participate in robotic precursor missions should opportunity arise**
  - Site characterization and resource mapping
  - Subscale ISRU demonstrations for subsequent mission risk reduction
  - Outpost 'dress rehearsal' mission



# Why Perform Analog Field Tests?

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## Concrete Benefits of Field/Analog Testing

- Mature Technology
- Evaluate Lunar Architecture Concepts Under Applicable Conditions
- Evaluate Operations & Procedures
- Integrate and Test Hardware

## Intrinsic Benefits of Field/Analog Testing

- Develop Partnerships
- Develop Teams and Trust Early
- Develop Data Exchange & Interactions with International Partners
- *Outreach and Public Education*



# ISRU Analog and Field Test Site Requirements

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- **Minimum vegetation**
- **'Good' Weather**
  - Minimum rain and wind
  - Lots of sunlight
  - Reasonable temperatures (unless specifically needed for test objectives)
- **Open and relatively flat areas for 'Outpost-like' operations**
- **Varied terrain and rock features for resource prospecting and science operations**
- **Local material with similar physical characteristics to the Moon for excavation and site preparation**
- **Local material with similar mineral characteristics to the Moon for resource prospecting, oxygen extraction, and processing**
- **Local material that can be modified, processed, and permanently altered for site preparation and construction**



# Why Perform an ISRU Field Demo? Why Hawaii?

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## Why an ISRU Field Demo?

- Demonstrates lunar ISRU feasibility for Outpost needs at relevant Outpost scale operations.
- It forces design decisions to be made and gets hardware out of the laboratory
- Initiates integration of ISRU with other NASA Technology Projects and Science Mission Directorate for requirements, schedules, hardware, and operations
  - Begin standardizing interfaces, connections, and modular units
- Initiates opportunity for collaborations with International Space Agencies in non-flight situation (CSA, JAXA, DLR) and allows data and ITAR issues to be worked
- Builds teams and trust which will be important when actual flight hardware and development issues arise in the future

## Why A Volcanic Site in Hawaii?

- Terrain, rock distribution, and material/soil provides good simulation for lunar polar region, and tests hardware and operations beyond ability of laboratory and 'rock yards'
  - Apollo field testing "deemed most relevant site" by Astronauts
- Infrastructure is very close to site of testing minimizing time wasted
- PISCES is 'hosting' ISRU field test. Performing all work on permits and establishing site, arranging food/lodging, providing hardware assembly and checkout facilities, providing site infrastructure and support (tents, toilets, food, etc.)
- State of Hawaii and Innovative Partnership Program (IPP) are providing funding to significantly reduce cost
- Central location for US, Canada, and Japan to partner and ship hardware



# ISRU Field Test – Hawaii 2008



## Key Field Test Personnel

- Jerry Sanders & Bill Larson ISRU PM
- Tom Simon, OPTIMA lead
- Frank Schowengert, PISCES
- Rob Ambrose HRS PM
- Jackie Quinn, RESOLVE lead
- Michel Doyon, CSA

## Field Test Objectives

- 1. Mobile Resource Characterization & Oxygen Demonstration (RESOLVE/Scarab)**
  - Demonstrate resource prospecting, site surveying, and oxygen production
  - Demonstrate hardware integration and mobile surface operations
  - Opportunistic Demos: Hand-held Raman spectrometer (CSA); Mossbauer spectrometer (JSC) on Cratos rover; CHEMIN XRD/XRF (ARC/LANL)
- 2. OPTIMA (ISRU End-to End Outpost Scale Oxygen Production & Storage Field Test)**
  - Demonstrate excavation and regolith delivery to ISRU plant
  - Demonstrate oxygen extraction from regolith at outpost production rate
  - Demonstrate system integration, modularity of modules for swapping, and surface operations
  - Opportunistic Demo: Cryogenic oxygen/methane storage, feed, and thruster firing
- 3. Demonstrate partnership with State of Hawaii and Pacific International Space Center for Exploration Systems (PISCES)**

## Customers

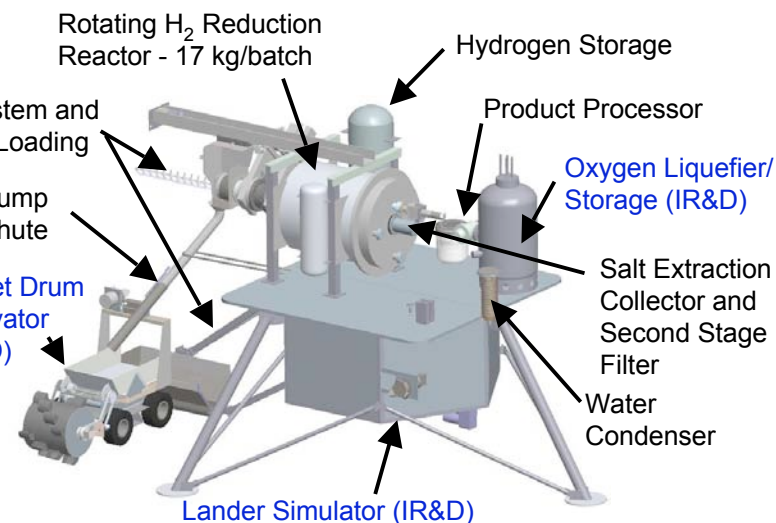
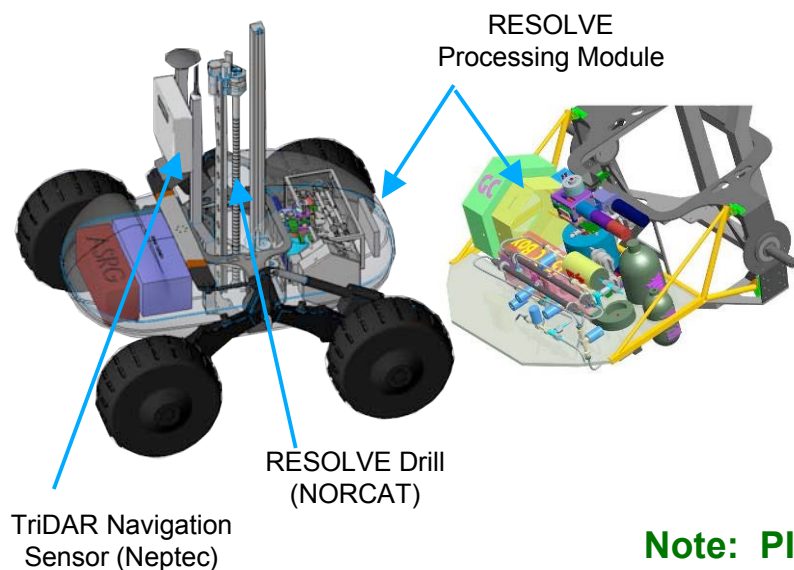
- CxPO Lunar Surface Systems Office
- SMD, OSEWG, and ESMD Lunar Scientist
- NASA ESMD Advanced Capabilities & Directorate Integration Office
- NASA Office of External Relations



# ISRU Field Test Hardware for Nov. 2008



## RESOLVE/Scarab Rover

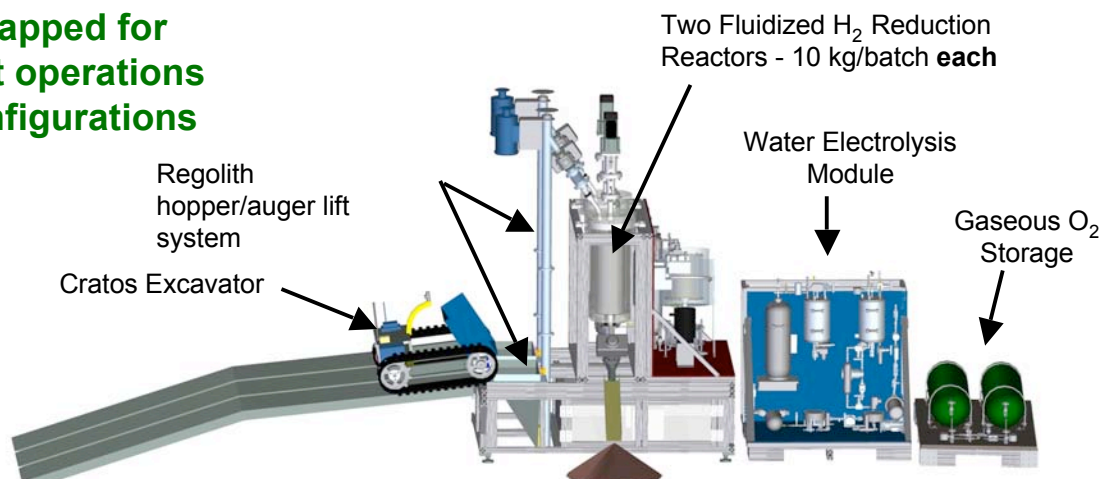


## LMA PILOT H<sub>2</sub> Reduction System

**Note: PILOT and ROxygen modules can be swapped for different operations and configurations**



**NASA Cryo O<sub>2</sub>/CH<sub>4</sub> Storage-Feed System & 25 lbf thruster/igniter (Optional Test)**



## NASA ROxygen H<sub>2</sub> Reduction System



## Education and Public Outreach



### ■ Education Outreach

- NASA personnel plan to visit several schools during out field test campaign.
- Presentations focus on NASA's return to the moon and learning to live off the land.
  - Need for Math and Science Education will be emphasized



### ■ Public Outreach

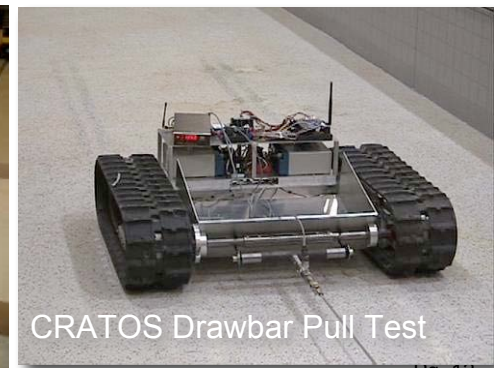
- NASA will provide presentations in the Center's Auditoriums on America's return to the moon.
- Demonstration of NASA's robotic excavation vehicles will be scheduled at the 'Imiloa Astronomy Center in Hilo
- Students will be given an opportunity to operate the rovers



Scarab with Canadian Tridar Navigation System



Lockheed Martin  
Bucket Wheel Excavator



CRATOS Drawbar Pull Test



## **Backup Slides**

### **Experiment Details and Objectives**

# Mobile Resource Characterization and Oxygen Production Demonstration





# Mobile Resource Prospecting & Oxygen Production Objectives

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- **Demonstrate resource prospecting, site surveying, and oxygen production demonstration activities**
  - Demonstrate Scarab rover carrying RESOLVE and TriDAR camera to multiple locations over varying terrain
  - Demonstrate dark navigation
  - Perform sample acquisition, transfer, metering, and sample evaluation
  - Perform RESOLVE resource prospecting operations (drilling, crushing, volatile extraction, and capture) at multiple locations – 1 minimum, 3 nominal, 5 maximum
  - Demonstrate remote drill site selection (Neptec TriDAR camera) and RESOLVE drill operation from CSA.
- **Demonstrate hardware integration and mobile surface operations**
  - Integration of complete RESOLVE unit onto Scarab rover
  - Integration of TriDAR camera onto Scarab rover
  - Build relationships and interactions with other NASA projects, industry, academia, international partners, and SMD
- **Opportunistic Demos:**
  - Evaluate incorporation of data from other science instruments with RESOLVE and TriDAR through SMD Moon and Mars Analog Mission Activity (MMAMA) and Canadian Space Agency (CSA)
    - Raman spectrometer (CSA)
    - Mossbauer spectrometer on Cratos rover to evaluate material before/after processing
    - Mini-CHEMIN XRD/XRF (hand carried) to evaluate material after processing (MMAMA)



## Mobile Resource Prospecting & Oxygen Production (RESOLVE/Scarab) Tasks

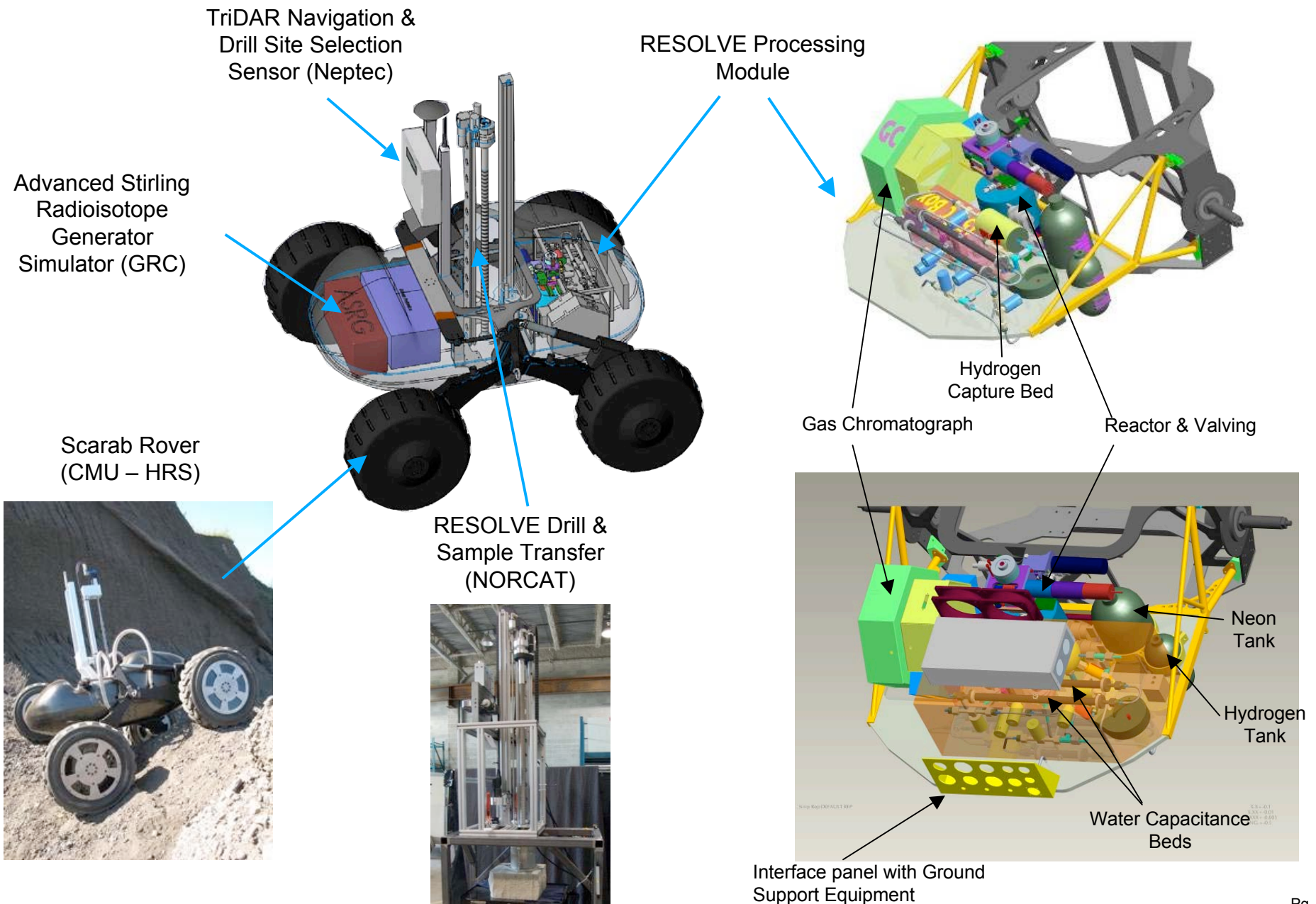
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- Demonstrate roving over multiple terrain features with complete RESOLVE-science payload
- Demonstrate dark navigation of Scarab over varied terrain and rock distribution
- Demonstrate drill site selection using TriDAR and Raman spectrometer via remote analysis at CSA PTOC
- Demonstrate remote operation of drill and sample transfer operations at CSA PTOC
- Demonstrate end-to-end operation of RESOLVE package
  - Min. of two times for resource prospecting: drilling, sample transfer, crushing, heating, volatile characterization; Max. 5 times
  - Min. of one time for oxygen extraction from regolith; Max. 3 times



# Mobile Resource Characterization & Oxygen Demonstration Hardware





# **OPTIMA: Outpost Precursor Testbed for ISRU & Modular Architecture**



# OPTIMA - Outpost Scale Oxygen Production & Storage Objectives

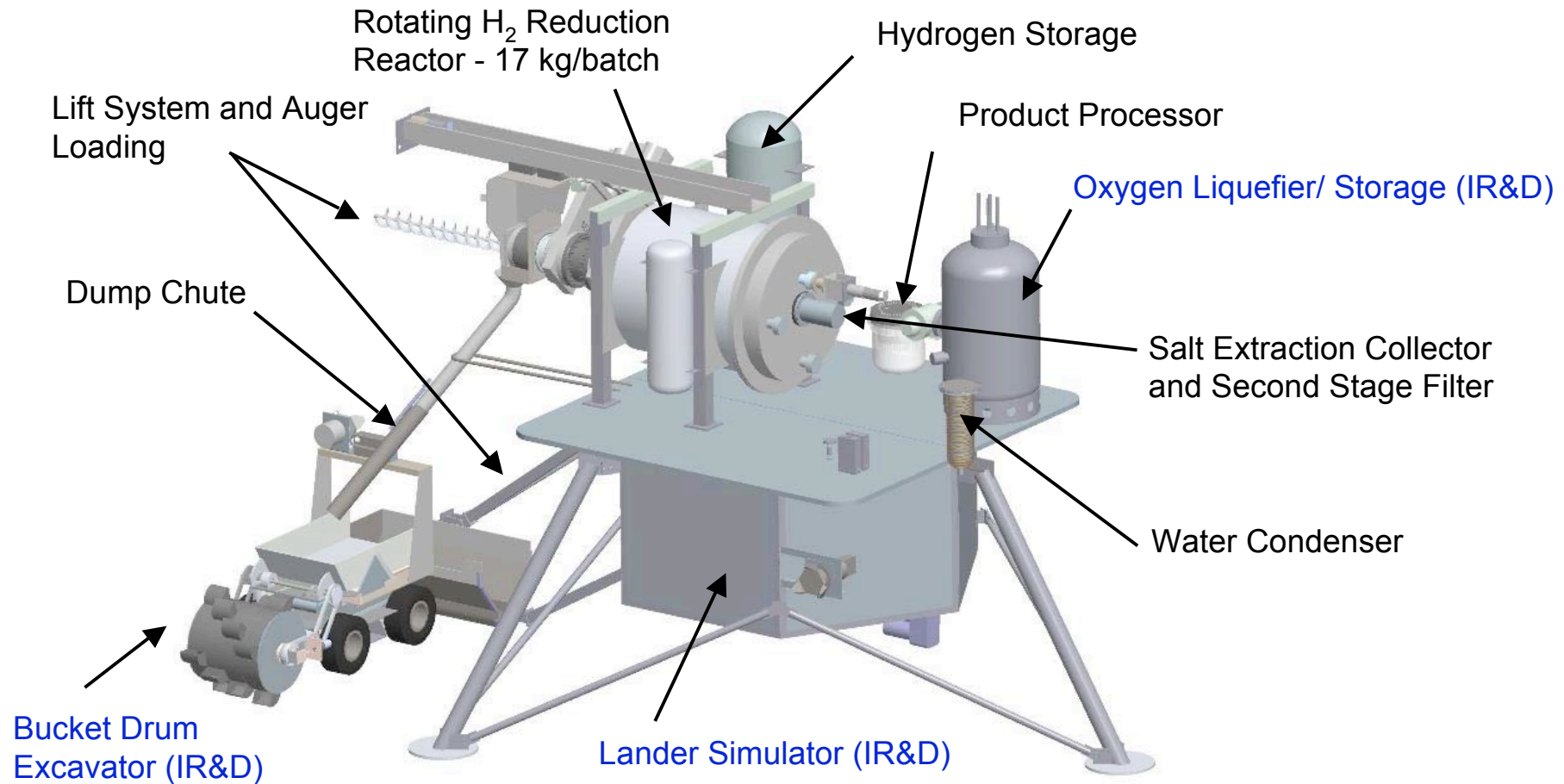
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- **Demonstrate excavation and regolith delivery to/from ISRU plant**
  - LMA Bucketwheel rover (IR&D)
  - NASA Cratos rover
- **Demonstrate oxygen extraction from regolith at outpost production rate**
  - NASA ROxygen fluidized bed + auger hydrogen reduction reactor makes oxygen at ~660 kg/year (2/3 scale for Outpost)
  - LMA PILOT rotating hydrogen reduction reactor makes oxygen at 250 kg/year (1/4 scale for Outpost)
- **Demonstrate oxygen storage**
  - LMA liquefaction and storage with cryocooler and vacuum-jacketed tank (IR&D)
  - NASA moderate pressure gas storage
- **Demonstrate system integration, modularity of modules for swapping, and surface operations**
  - Demonstrate feasibility of end-to-end oxygen extraction from regolith
  - Demonstrate open architecture and modular approach with standardized interfaces between modules
  - Integrate hardware from different projects and industry
  - Build relationships and interactions with other projects and industry
  - Begin discussions with international partners
  - New NASA and industry partners for subsequent demonstrations



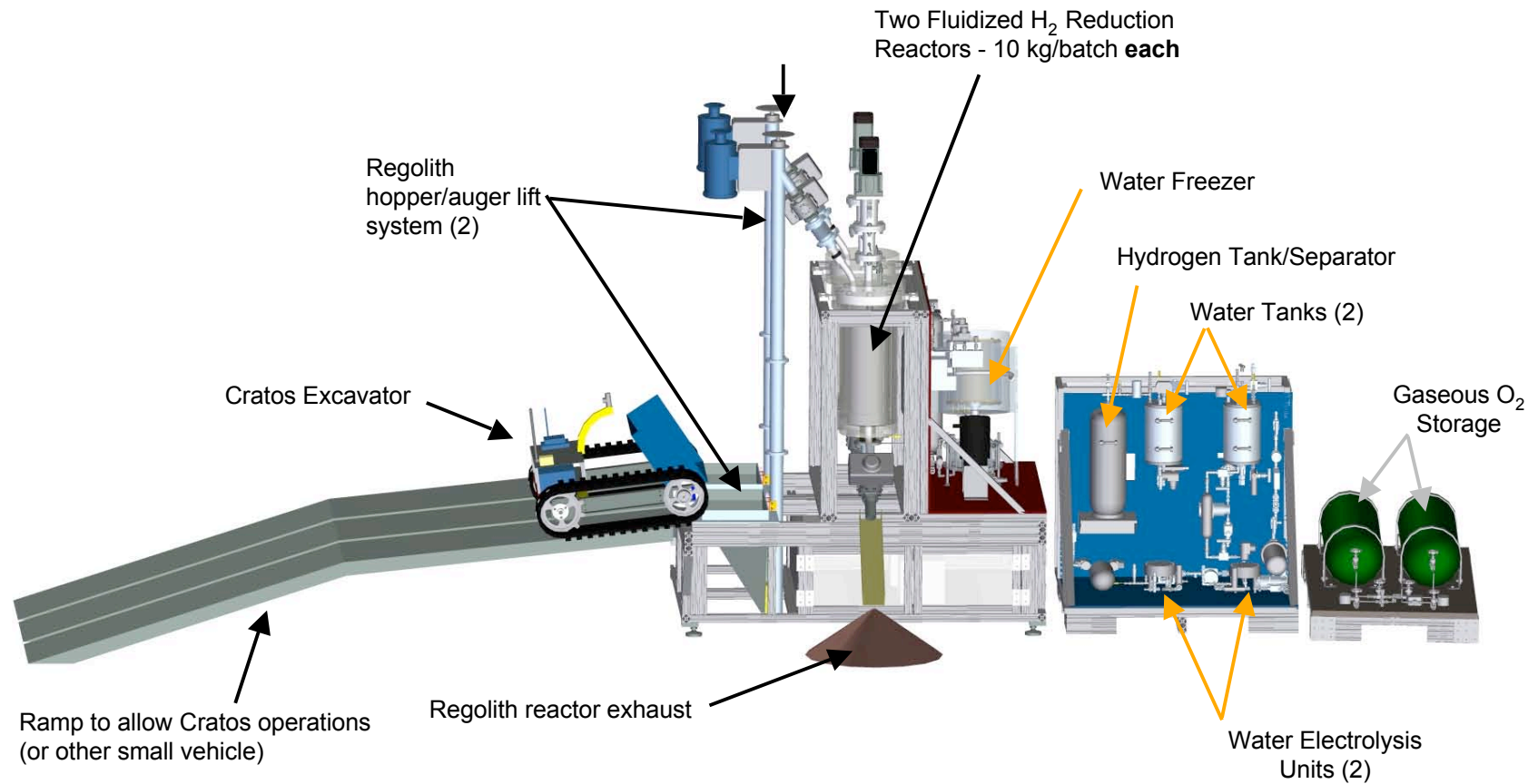
## PILOT Field Test Hardware



**PILOT – Precursor ISRU Lunar Oxygen Testbed**



# ROxygen Field Test Hardware



**NASA ROxygen H<sub>2</sub> Reduction System**



## OPTIMA ROxygen & PILOT Tasks



- Demonstrate excavation and material delivery to plant and removal of spent regolith;
  - Increase distance and terrain complexity between plant and excavation site each day
- Demonstrate regolith processing to extract oxygen
  - Min. of 4 hrs on one day; nominal 8 hrs per day
  - Max. of 8 hrs/day for 5 days
- Demonstrate oxygen separation and storage
  - Liquefaction and cryogenic storage
  - Moderate pressure gaseous oxygen
- Opportunistic Demos
  - Demonstrate alternative oxygen liquefaction and storage
  - Hot fire a  $\text{LO}_2/\text{LCH}_4$  RCS 25 lbf thruster igniter
  - Mossbauer spectrometer on Cratos to measure iron before and after processing



**NASA Cryogenic RCS Thruster Testbed  
(Planned Add-on)**

**“Dust to Thrust”**